
Black Holes in Orbit

Summary

Students are introduced to the basic properties, behavior and detection of black holes through a brief discussion of common conceptions and misconceptions of these exciting objects. They “act out” a way black holes might be detected through their interaction with other objects. In this activity, girls represent binary star systems in pairs, walking slowly around one another in a darkened room with each pair holding loops of wire to simulate the gravitational interaction. Most of the students are wearing glow-in-the-dark headbands to simulate stars, some are without headbands to represent black holes, and a small set of the black holes have flashlights to simulate X-ray emission.

Objectives

- ★ To learn the basic properties of black holes, including:
 - ★ Escape velocity
 - ★ Gravitational interactions
 - ★ Accretion disks
- ★ To consider black holes less mystifying
- ★ To brainstorm ways to observe objects or phenomena which cannot be seen directly
- ★ To be introduced to basic X-ray physics

Materials

- ★ Tennis ball
- ★ Set of density blocks (objects of the same size and different weights) *
- ★ Loops of heavy gauge wire, ~ 36 inches in circumference (5-6)
- ★ Loops of heavy gauge wire, ~ 60 inches in circumference (5-6)
- ★ Glow-stick necklaces (one per student) **
- ★ Flashlights and batteries (6)
- ★ Cellophane or tissue paper to cover flashlight lenses
- ★ Tissue paper party decorations – 2 large balls, 1 large disk ***

** Information about where to purchase this can be found in Appendix B.*

*** In the past, we have used headbands with glow-in-the-dark stars on them. They had the advantage of being cheap and reusable, but proved difficult to see unless the room was 100% dark. This prompted us to switch to glow-stick necklaces. There is certainly room here for substitutions to be made, but the key is to have something that emits light that can be seen no matter which direction the student is facing (such as a necklace, a headband, or a belt).*

**** Any other objects of the same general shape can be substituted for this.*



The supplies for this session are laid out on a table.

Other Requirements

- ★ A room with adequate space to move around for the activity
- ★ A room that can be darkened (preferably completely darkened)

Background

On Earth, when you throw a ball into the air, it falls back to the ground because the Earth's gravity pulls the ball back down. The higher and faster you throw the ball, the longer it will take to fall back to the ground. The same principle applies to the cannon balls in the following image. The faster the cannon balls are shot, the farther they will go.



Faster cannon balls getting farther as they are shot off a tower.

If you could throw the ball with enough speed, it would not come back down, but would continue around the planet (in orbit.)



Illustration showing that if a cannon ball were shot fast enough, it would go around the Earth.

For each body in the Universe there is a certain speed at which an object must travel in order to escape the body's gravitational pull. This special speed is called the "escape velocity," and it differs for each body depending on its mass. Any object traveling slower than the escape velocity will fall back to the surface, but any object traveling faster will continue moving away from the body. The reason we are able to send rockets into space is because they are accelerated to speeds greater than Earth's escape velocity. On Earth, this speed is 11.1 kilometers per second (or 40,200 kilometers per hour), which is the same as 7 miles per second (or 25,000 miles per hour). Other objects have different escape velocities, depending on their mass – the more massive something is, the higher the escape velocity from that object will be. For example, the moon is less massive than the Earth, and so its escape velocity is only 2.4 kilometers per second (1.5 miles per second). Moreover, the Sun, which is much more massive than the Earth, has an escape velocity of 621 kilometers per second (386 miles per second), forcing objects to travel at much higher velocities in order to escape its gravity.

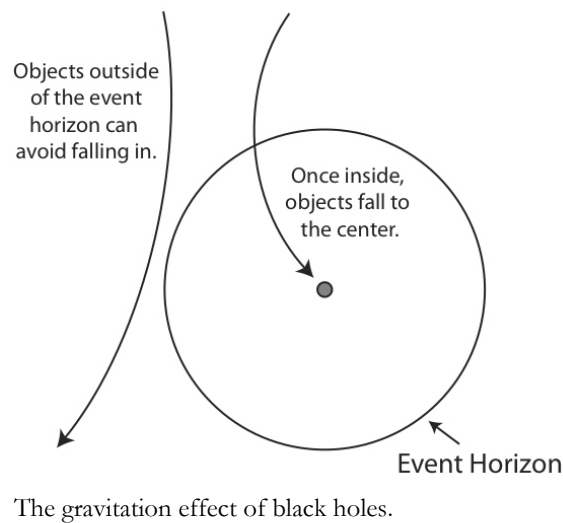
Black holes are such dense objects, with such an incredibly strong gravitational pull, that their escape velocity exceeds the speed of light! Since Einstein showed that nothing can travel faster than light, then nothing can escape the gravity of black holes, not even light!

There is strong observational evidence for two types of black holes – stellar mass black holes, which are typically 5-15 times as massive as our Sun and are formed when large stars explode as supernovae and collapse; and supermassive black holes that are millions to billions times the mass of our Sun and are always found at the centers of galaxies. For example, our own galaxy, the Milky Way Galaxy, has a central supermassive black hole that is 4.3 million times the mass of our Sun, but only about the size of our Solar System. The formation of these supermassive black holes is still mysterious and the subject of a great deal of current research.

A third type of black hole, known as an intermediate mass black hole, is also thought to exist. These black holes are predicted to weigh about 1000 times the mass of our Sun and are an active area of research.

The event horizon of a black hole is the spherical boundary between the black hole and the outside Universe, within which any object (or even any light ray) would have to exceed the impossibly high escape velocity to avoid falling inwards towards the center of the black hole. It is not a physical boundary, but is instead the 'point of no return' in the sense that that once any object strays inside of the event horizon, it will never be able to escape the black hole's gravity, and will fall into the very center of the black hole. In

this region the infalling matter is destroyed and our current laws of physics probably become invalid.



It is important to realize that outside of the event horizon a black hole exerts the same gravitational force on nearby objects as any other object of the same mass would. For example, if the Sun were magically crushed until it had a radius of only 3.2 kilometers (2 miles), it would become a black hole, but the Earth would feel the same gravitational force and hence remain in the same orbit as before the Sun was crushed. In this sense, black holes are not cosmic vacuum cleaners that reach out and suck everything into them. Thankfully, our Sun is not big enough to ever become a black hole, so don't worry about that!

Not surprisingly, black holes can be very challenging objects to detect as space is also black! Astronomers cannot observe black holes directly, but instead detect them through their gravitational effect on nearby gas and stars. A particularly important example is when a normal star (like the Sun) is orbiting a stellar-mass black hole. In this case, the gravity of the black hole can pull gas off the surface of the star and into itself. As the gas spirals into the black hole, it gets extremely hot and emits a large amount of X-rays, which modern X-ray telescopes can detect. Observations can also reveal how the normal star “wobbles” as it orbits around the unseen black hole, and so reveals the black holes presence.

Preparation

1. Wire loops: approximately 10 minutes
Cut and shape the wire into 5-6 medium sized loops (approximately 36 inches in circumference) and 5-6 large loops (approximately 60 inches in circumference). Make a figure 8 shape with both loop sizes, attaching two of the same size together (electrical tape works well for this). The students will use this to simulate the gravitational pull at different distances between stars and black holes.
2. Flashlights: approximately 5 minutes
Cover the lenses of the flashlights with cellophane or tissue paper, and tape this into place.
3. Darken the room: variable
The room should be capable of going from brightly lit to dark so that the glow stick necklaces can be seen effectively. Sometimes this means lights or light leaks must be covered. Dark black plastic trash bags and duct tape have proven useful for this. A ladder is often required to reach the lights in an institutional building with high ceilings. The assistance of a custodian or building manager is

often required, so it is important to arrange for this in advance, and to return the room to the original condition when finished.

Activity

Talking Point: Initial Ideas about Black Holes

Ask the girls what they know about black holes. Allow them to brainstorm their ideas.

If it doesn't come up on its own, ask if they know why we call them black holes. They will probably say it is because they are black, but why are black holes black?

If black holes are black and space is black, how do we find them?

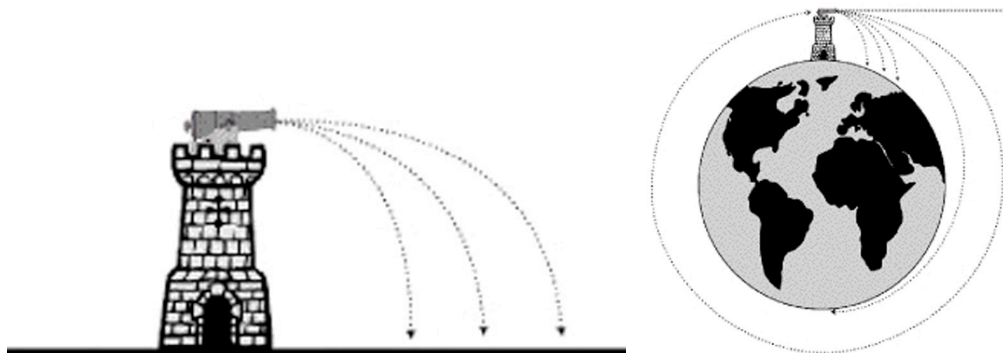
Tell them that we will be exploring these questions.

Talking Point: Orbits

If an object orbits another object, it goes around that object in a fairly fixed circle or oval. The Moon orbits the Earth, the Earth and other planets orbit the Sun, and sometimes two stars orbit each other. When this happens, we call them binary stars. Roughly half of the stars visible in the sky are binary stars, so this is relatively common. You can demonstrate the idea of an orbit using the two round party decorations (or any other round objects) and showing them going around each other.

Demonstration: Escape Velocity

Use the example of a tennis ball to help explain this concept. If you toss a tennis ball in the air, it falls back down to the ground. Ask them if they know why – the answer is gravity. If you toss the ball a little bit harder and faster, it takes a bit longer to fall back down to the ground. Theoretically, if you could toss this tennis ball hard enough and fast enough, it would not fall back down. The illustration below of a cannonball being shot from a tower also illustrates this idea. As the cannonball is shot with more speed and force, it goes farther and farther. Eventually, with enough speed and force, the cannonball goes into orbit, and with even more force, the cannonball escapes entirely.



Faster cannon balls getting farther as they are shot off a tower. Hypothetically, if one were shot fast enough, it would go into orbit.

The minimum speed that anything must be going in order to escape an object's pull is known as the

escape velocity, and it varies depending on the mass of the object. The speed you would have to throw the tennis ball to escape from the Moon is less than the speed you would have to throw it on the Earth because the Moon is smaller and less massive than the Earth. Likewise, the escape velocity for the Sun is much greater than the escape velocity for the Earth because the Sun is much more massive than Earth.

Demonstration: Density

Ask if the students know what the word “density” means. Most likely they will have some idea. Density is a physical property that can be related to an object’s size and mass/weight. Ask them to think of examples of everyday objects that are very small and heavy (high density) or large and light (low density).

You can also pass around the element/density cubes or ask for volunteers to come to the front to handle them. These cubes are all exactly the same size, but since they are made out of different materials with different physical properties, they have different weights. This is an example of density. The cubes that weigh more have a higher density than those that weigh less. There is more “stuff” crammed into the heavier cubes.

Talking Point: What is a Black Hole?



A black hole is an object so massive that the escape velocity is greater than the speed of light. This means that nothing, not even light, which is the fastest thing in the Universe, can ever escape from inside a black hole. The fact that no light can escape from these objects is why we call them *black* holes.

Black holes are also very small in size. Combined with their high mass, this means that black holes are incredibly dense. In fact, they are the densest things that we know about in the Universe.

Talking Point: Observing a Black Hole

If not even light can escape a black hole, then how can we know they’re there? After all, space looks black as well. The primary way that we observe black holes is by the effects of gravity. If a star in a binary star system becomes a black hole, it will still have another star orbiting around it. When we observe such a star apparently orbiting around nothing that can be seen, we can assume that there is a black hole there. We will be doing an activity to demonstrate this idea.

Activity: Detecting Black Holes (approximately 15 minutes)

In this activity, students will play the part of stars and black holes, and observe how astronomers might be able to detect these objects, even though no light escapes from them. The numbers below assume a group of 25. You should adjust the numbers accordingly for the size of group and the space that you have.

It might be worthwhile to have some of the students on the sidelines as observers, and then have them switch with the participants, to give everybody a chance to both observe and act out a role. It is also useful to have a helper stationed by the light switch who can make the room go dark at will.

1. Demonstrate an orbit for the purposes of this activity by having two volunteers hold onto opposite ends of a figure-eight wire, pull it apart, and circle around each other.

2. Have 16 of the students wear glow stick necklaces. These students are “stars.” The rest of the students will not wear the necklaces, and will therefore be invisible in the dark; they will be the “black holes.”
3. Divide the students up roughly as follows:

3 of the students will be normal stars, without a pair, moving through the galaxy. 5 pairs of students will be normal binary star pairs orbiting around each other. 5 of the students with necklaces will pair with 5 students without necklaces to be normal star and black hole binary pairs. The remaining 2 students without necklaces will be black holes without a pair.
4. Each pair (whether a pair of normal stars, or a star and black hole pair) should be given a figure-eight wire. These wires come in different sizes to represent differences in how closely objects orbit each other.
5. Explain that the lights will be turned off and each pair of students will orbit each other. The unpaired students will be scattered around the room on their own. Make sure you tell all the students to circle or move slowly so as to avoid injuries. Practice the activity once with the lights on.
6. Turn the lights off and run through the activity. Have the students observe what happens. They will be able to see the stars because the glow stick necklaces give off light. The black holes, however, will be invisible (this is most dramatic when you can fully darken the room). Whenever a black hole is paired with a normal star, they will be able to see the star going around something, but they will not be able to see what. If two black holes are paired together, nothing will be visible. This is what happens with black holes in space.



Girls get set up in their pairs before the room gets dark.

Talking Point: Accretion Disks

Though black holes are not cosmic vacuum cleaners that wander around the Universe sucking things up, their gravitational pull does cause nearby material to be pulled in. This effect is most pronounced when the black hole is orbited by another star. As material spirals in towards the black hole, a disk is formed.

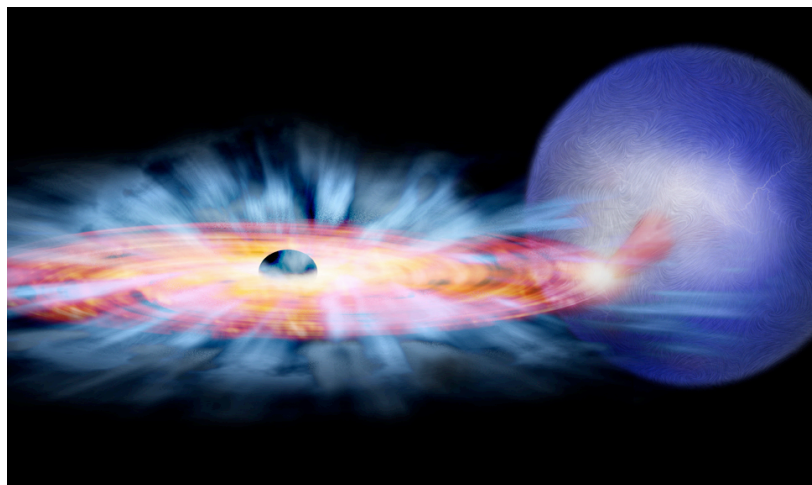
(You can use the tissue paper disk and ball to illustrate an accretion disk and an orbiting star.) The materials in this disk interact with each other, and as they do, friction causes them to become very, very hot. This causes light to be emitted, usually in the form of X-Rays. Since this light is generated by material *around* the black hole, rather than within the black hole, this light can escape, and we can detect it, giving us another way of detecting a black hole. At the end of this session there is an image of an artist's conception of an accreting black hole that can help with student visualization of an accretion disk.



A volunteer uses a party decoration to explain accretion disks.

Activity: Detecting Black Holes with X-Rays (5-10 minutes)

We will now repeat the above activity, but this time we will use covered flashlights to represent X-Ray emissions. It again might be worthwhile to have some of the students on the sidelines as observers, and then have them switch with the participants, to give everybody a chance to both observe and act out a role.



This is an artist's conception of a black hole with an accretion disk.

1. Any black holes who are paired with a star using the smaller sized figure-eight wire should be given one of the flashlights. One of the unpaired black holes should also be given a flashlight.

2. Turn the lights off and run through the activity once again. This time have the students with flashlights turn them on. Everybody should now be able to detect the X-Rays emitted by the accretion disks around some black holes. The idea here is that with the closer binary systems, the star and black hole are close enough for accretion to take place, i.e. the star “donates” some of its mass to the black hole and X-rays are emitted. This demonstrates a second way that scientists can detect black holes.

Talking Point: Wrap-up

Ask them questions based on this activity. Probe whether they now understand what a black hole is and how we detect them. While the leader does this, the helpers should go around and collect the flashlights and wire loops used in the activity.